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A MATTER OF DESIGN

MAKING SOCIETY THROUGH
SCIENCE AND TECHNOLOGY

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Smart materials: development of new sensory experiences through stimuli responsive materials

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Smart materials are materials that change properties according to stimuli, adapting to their environment. This makes them particularly interesting, to increase the performance of a product, and to enable new functionalities and new ways to interact with users. Some smart materials can affect the perception we have of objects. Existing smart materials have an action mostly on the visual and the tactile aspects. The most popular variations are based on colour changing materials, such as thermo/photo-chromic materials or thermo/photo-luminescent ones, and shape changing materials, such as shape memory alloys. These new materials will allow designers to introduce new sensory experiences in their products. For that, they need to know what differentiate these materials from common ones, which kinds of smart material exist, and to have some guidelines about how they can be used. This paper presents a tentative classification of smart material that relates to the way they can be used in product design. This is illustrated through some application examples of colour and shape changing materials.

Keywords: Smart materials; sensory experience; stimuli-responsive; industrial design

Introduction

To create innovation in product design, it is necessary to link the available technical knowledge, the actual industrial context and the cultures considered all together, in order to design object that are thinkable, feasible and accepted. 'Matter becomes capable of being integrated into design and in the end becomes part of a product' through supplying 'cognitive tools and

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cultural reference' (Manzini, 1989). However difficult with the expansion of synthetic materials and the rapid evolution of manufacturing processes, maintaining such a shared cultural, technical and industrial background was made possible after World War II through intensive collaboration across design and engineering in industries such as car manufacturing (Tovey, 1997) and the emergence of design as an academic discipline (Cross, 2001). With the emergence of nano-technologies and nano-functional materials, we are facing a particularly challenging situation, in which innovations developed in physics laboratories are being adopted and implemented in prototypes by designers before a proper engineering practice and 'design culture' (Cross, 2001) related to these materials has the time to be developed in industry. To create meaningful innovation, we need more than ever a strong knowledge transfer between the technical artifacts produced by physicists, their use in product offers by designers and their implementation in industry by engineers.

This is especially true when it comes to materials that show unusual behaviour, as it is the case with smart materials, for which the basic need for practical guidelines on how to use and implement them is particularly prevalent. This paper reports on an attempt to categorize and organize information on smart materials in a way comparable to what was achieved in engineering design for traditional materials twenty years ago (Cebon and Ashby, 1992).

Smart materials have the unique ability to respond to stimuli and adapt to their environment. Through this particularity, they offer new possibilities for designers, especially when it comes to the interaction between users and products. Though, there is a wide variety of behaviour among these smart materials: only separating these materials by type of input and output, there are already many different basic types of behaviours presented in this paper, with many possible behaviours for each type. Therefore, smart materials can be as difficult to apprehend in their whole as they are interesting for product design. To be able to take advantage of their unique properties and create new experiences for the user, knowing which smart materials exist and how they work is really important.

To try and represent effectively materials information on these materials, we have to reflect on the pioneering works of Ezio Manzini on the one hand (Manzini, 1989) and Mike Ashby (Cebon and Ashby, 1992; Ashby and Johnson, 2009). Starting from a different point of view, both converged towards the same outcome: to be meaningful to design or engineering, the

information on materials has to be expressed (and quantified whenever possible) in terms of functionality instead of just elementary physical properties.

In the case of smart materials, one important functionality that need to be identified and described is their stimuli responsive behaviour and the fact that they can connect different sub-spaces of the user experience that are normally disconnected with 'inert' materials (for example, with thermochromic materials, a thermal stimulus props a visual response, see figure 1).



Figure 1 Thermochromic ball: when heated by putting the hand on it, the ball changes colour, LRCHallcrest, source: <http://lcrhallcrest.com>.

This allows creating vivid multi-sensory user experiences, but will be difficult to represent using conventional 'Ashby-type' property charts. New ways of organizing, coding and representing materials data are needed to convey information on smart materials in a way which will be meaningful to designers.

The aim of this paper is to give an overview of existing smart materials, first through a proposition of classification that has been made as a first tentative of visualization of smart materials, and through different examples that would allow designers to have an idea of the possibilities given by smart materials. Especially, we have chosen to focus on materials that affect the user senses and their applications, since a user tends to evaluate the products relying on his emotions and perceptions, and will be more likely to appreciate a product that appeals to his senses (Passaro et al., 2013).

According to Desmet and Hekkert (2007), eliciting delight of one or more of our sensory modalities leads to a positive aesthetic experience which in turn favours a positive emotional response and generates affect toward the product.

What are smart materials?

General description

Smart materials are materials that change properties according to stimuli: under a certain input, they produce a predictable and repeatable response, or output (figure 2).

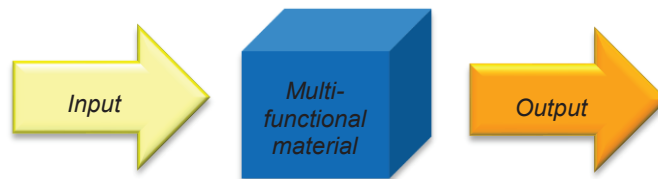


Figure 2 Basic functioning of smart materials.

The input can be either specific wavelengths of light, temperature changes, movement, deformation, pressure, chemical concentration, electric field or magnetic field, while the output produced can be changes in colour, light, temperature, deformation, stress, stiffness or viscosity, electric field, magnetic field or electrical resistance.

According to Addington and Schodek (Addington and Schodek, 2005), most of these smart materials have five characteristics in common: *immediacy*, *transiency*, *self-actuation*, *directness* and *selectivity*. The *immediacy* means these materials react as soon as the stimuli appear, i.e. they have an immediate response. The *transiency* is related to the fact that they react to more than one environmental state, and have different properties depending on these various environmental states. *Self-actuation* means the special properties are internal of the materials, and are not produced by some external actions on the materials. *Directness* represent the fact the response of the material is local, and the output is produced at the point the input was given. Last of all, *selectivity* qualifies the predictable and repeatable characteristic of the response, so a single environmental state can only lead to a unique and constant response of the material. (Addington and Schodek, 2005).

Classification

Although they have these common characteristics, there are many types of smart materials, and each type will have a different interest for designers

and users. To better understand the range of potential uses, a classification is needed.

A possible way to sort these materials is to separate them by input and output, which represents their main functionality, in terms of materials selection criteria (Ashby et al., 2002). This is illustrated by the graph in figure 3, which links the input, on the left hand side, with the output on the right hand side for each type of functional materials.

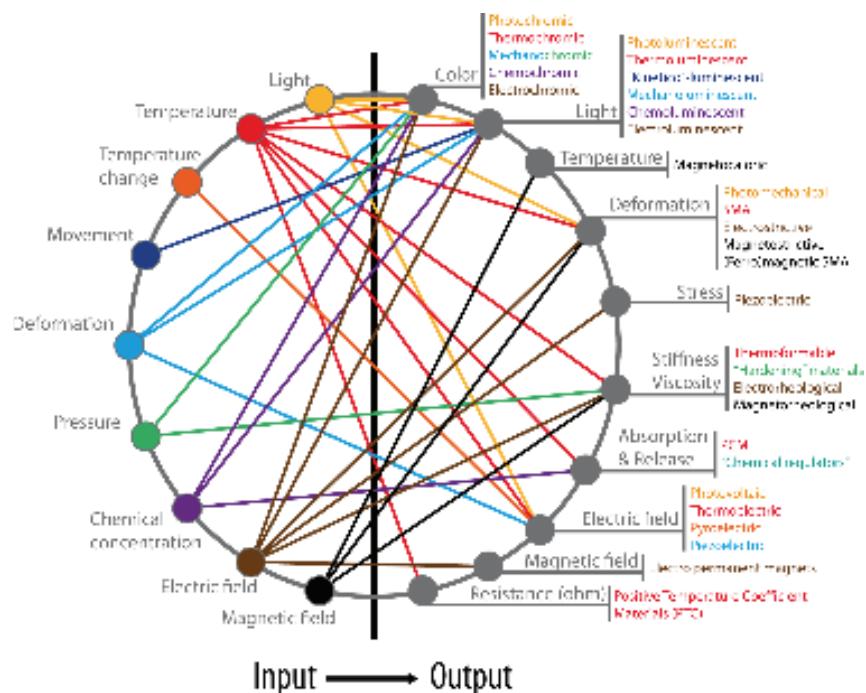


Figure 3 One possible classification of smart materials.

The different types of materials are represented by a link between the input and output associated to them. For example, photochromic materials are represented by the link between the input 'Light' and the output 'Colour'.

The graph can be useful to explore the possibilities offered by smart materials: as they show numerous different behaviours, it can be difficult to envision all the possibilities offered by these materials, and such a map can






provide first guidelines. One can look at the materials that correspond at a given input he wants to use to switch on the object or add an additional functionality, or he can see which materials are able to produce the desired response, and which type of input they need to be activated. Finally, one can simply use the map to get basic information about what kinds of smart materials exist, as a source of inspiration.

Such a graph could also be used to know which classes of smart materials can be adapted for an application in a given project.

Another way to use such a graph is to pick up the most appropriated type of material given the interaction one wants the object to have with the user. For example, if a designer wants an object to react to surrounding temperature by changing shape, a possible way is to use Shape Memory Materials (SMM). Several options are available to achieve this effect, and practical constraints such as, e.g.: shape, size, required production rate, ... will decide on the final choice (e.g.: Ni-Ti shape memory alloys).

Additionally, some of these materials exhibit a bi-directional response: they can react to an input creating an output, but also react to the former output and have an effect on the input. For example, piezoelectric materials respond to an electric potential by generating a deformation, and respond to a deformation by producing an electric tension. Therefore, these bi-directional smart materials can be used in a different way than the other ones, whose response is mono-directional. A list of such reversible smart materials is listed in Table 1.

Table 1 Smart materials having a bi-directional effect.

Type	Input		Output
Piezoelectric	Deformation		Electric field
Pyroelectric	Temperature difference		Electric field
Thermoelectric	Temperature difference		Electric field
Electrostrictive	Electric field		Deformation
Magnetostrictive	Magnetic field		Deformation

Although it is important to know what kinds of smart materials exist to understand the possibilities they offer, it might not be totally sufficient to know how to use them. It can be useful to know why and how the material exhibits its particular behaviour. Another way to envision the possibilities is to look at already existing applications. These two points will be the topic of the second and third parts of this paper, focusing on materials that directly affect the user's senses.

Smart materials vs. common materials

The varying properties of smart materials make them fundamentally different from common materials. Indeed, common materials are most often used as a medium to give fixed properties to an object and a change of properties or behaviour with their environment is often seen as a difficulty that has to be dealt with, rather than an opportunity to provide additional functionality. In the case of smart materials, these properties become variable: the material will respond by itself to a particular event in its environment, and at the same time give information, interact with and/or entertain the user. By taking advantage of the versatility of these materials, designers can imagine a new relation between the user and the object. As stated by Passaro et al. (2013), the sensory properties of a product are essential in the user's evaluation and attachment toward it. Therefore, making the product's sensory properties reactive present a great advantage to amplify the interactions between the user and a product.

Another advantage of smart materials over common ones is that their response is immediate and simple, while through common materials a complex system or interface would be required to give the same response, often with a larger delay. This opens the possibility to a new way of conveying 'material immateriality', as recently defined by Arnall (Arnall, 2014).

However, smart materials are not yet commonly implemented in industrial products. There are different reasons for that: the first one is that these materials can be complex to process and produce because there is no shared expertise on how to use them efficiently in industry. Thus smart materials have to be considered separately from other materials, but still need to be compared with and put into perspective with conventional solutions when considering design options. Indeed, on the strict ground of feasibility, it is not straightforward to decide which solution between an innovative smart material and a system of conventional materials will be more relevant and efficient for a given application. This again highlights the

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need to express their characteristics in terms of *functionality* instead of just *properties*.

Another point that can prevent their widespread use and development in the industry is the perceived risk of using very new materials. For example, it can be difficult to check or estimate the durability properties for new materials, and if it matches with the life expectancy of the product. Finally, some of the functional effects exhibited by smart materials can decrease in intensity throughout their lifetime, but this evolution is rarely documented in a useful (quantitative) way.

Smart materials that directly affect senses

If we focus on making the sensory properties of an object variable and interactive, several classes of materials become more interesting than others. It is especially the case for colour changing, light-emitting and shape changing materials, which variations affect directly the perceptions of the user.

Colour changing and light-emitting materials

These materials have a direct effect on the visual appearance of an object, and present a large variety of possible inputs, therefore they can be used in a wide variety of applications. For both colour changing and light-emitting materials, possible inputs are light (photochromic, photoluminescent), change in temperature (thermochromic and thermoluminescent), deformation or pressure (mechanochromic and mechanoluminescent), chemical concentration (chemochromic and chemoluminescent) and electric field (electrochromic, electroluminescent and LEDs). Some materials also change colour when they are submitted to a pressure change.

Shape changing materials

As for colour changing materials, there are several types of existing shape changing materials. The most well-known are shape memory alloys and polymers that recover their initial shape when heated. Other shape memory materials exists that regain their shape under a magnetic field, pressure, a chemical concentration or light (Del Curto, 2008).

In shape memory alloys (SMA), the shape memory effect is due to a change of phase inside of the material: the material is in a phase, or form, called martensitic when cold, and in an austenitic phase when heated at a

certain temperature. Since these phases have different atomic structures, the material is rearranging itself when heated and recovers its initial shape. Depending on the SMA, the temperature of phase change is different. As illustrated in the figure 4, this effect can be either one- or two-ways: in the one-way version, the SMA can be deformed by the user in its cold state and will recover its initial shape when heated; in the two-way version, it will have two preset shapes, one when cold and one when heated, and will switch to one form to the other depending on the temperature (Van Humbeeck, 2008).

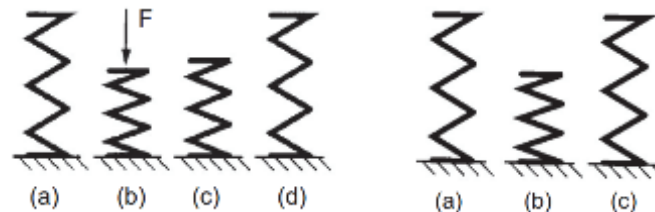


Figure 4 Shape memory alloy (Van Humbeeck, 2008). Left: One-way configuration – when submitted to a deformation in its cold state, the material will stay deformed (a \rightarrow b \rightarrow c). Then, when heated, it will recover its initial shape (c \rightarrow d); Right: Two-ways configuration – the material change shape spontaneously when cooling down from one preset form to another (a \rightarrow b), and return back to the previous form when heated (b \rightarrow c).

Apart from this shape memory effect, other materials exhibit a reversible deformation when submitted to specific stimuli. It is the case for photomechanical materials, that change shape under light or UV light, electrostrictive and piezoelectric materials that deform in reaction of electricity, and magnetostrictive materials, that react to magnetic field. Among these, the piezoelectric, electrostrictive and magnetostrictive effects are bi-directional.

How to use smart materials to create new interactions between products and users

As there are many existing types of smart materials, there are also many ways to use them. Starting from the knowledge of the different available effects, a designer can imagine new features for his product, which would not be possible to achieve otherwise. These new features can be purely aesthetic, and aimed at creating surprise for the user, but they can also be

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functional, allowing the object to adapt by itself to the environment, either to give messages to the user or to provide him or her with more convenience.

Applications of thermochromic materials

A popular type of smart materials that has already been used in large scale production for some times is the thermochromic class. These materials are commonly used for entertaining applications as furniture, clothes, hidden messages and so on, and for functional uses to give information to the user, as a warning for example. The thermochromic effect can be added to a large range of support materials as dyes, paints or pigments (Ritter, 2007). Depending on the chosen thermochromic element, the change of colour can be either a continuous gradient of colour or a unique and rapid change at a precise temperature, as shown in figure 5.

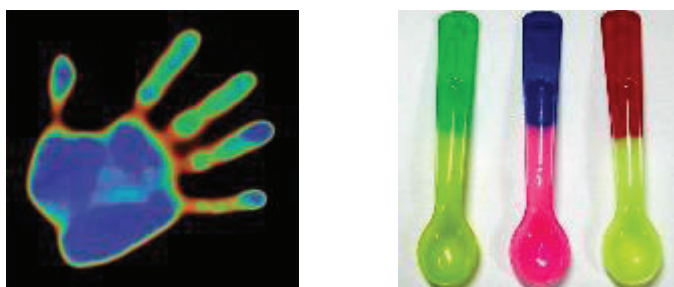


Figure 5 Thermochromic materials. Colour gradient or sudden change at a given temperature. Left: Liquid crystal ink that changes colour between 25 and 30°C, passing through all the visible spectrum, H.W. Sands Corp, source: www.hwsands.com/; Right: Thermochromic spoons, Master Batch, source: www.newcolorchem.com.

The colour gradient versions can be easily used as thermometers. It has been often used to quickly measure body temperature with more comfort than usual thermometers, and measure a room temperature in an alternative way. Some more playful applications, such as the mood rings and mood tests that use the change of colour induced by the body temperature variation to supposedly indicate a person's mood have also been proposed.

For the one-off colour change version, the object changes its colour at a given temperature that is different for each thermochromic material. This allows programming the final object to give a signal when a temperature is

reached, either to give a warning or to indicate that a product is ready to be consumed or used. For example, the spoons presented on figure 5 change colour to indicate the food is too hot to feed a baby; other uses can be to indicate to show on the kettle that the water inside is boiling, or that a drink inside a can is cold enough. Like in the colour gradient case, other uses of this colour changing properties can make an object more directly interacting with the user: especially, when the change in colour is scaled at body temperature, artefacts become sensible to touch and respond at the contact of the user. For example, thermochromic paints and inks can be used on tables and seats to indicate that someone has been there, a flu mask that indicates the user has a fever (Figure 6):

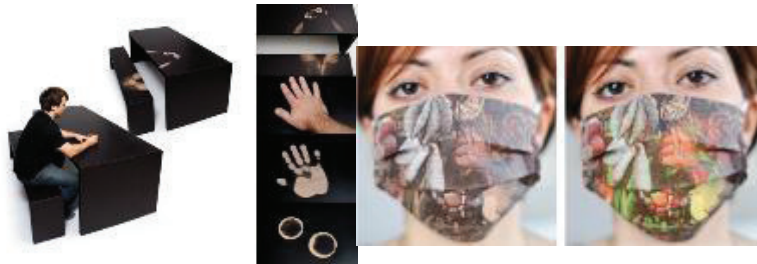


Figure 6 Left: Thermochromic table, 'Linger A Little Longer' by Jay Watson design, source: www.jaywatsondesign.com/; Right: Thermochromic flu mask, Kooroshnia Marjan, University of Borås. Swedish School of Textiles, source: <http://hdl.handle.net/2320/10207>.

Applications of photochromic materials

Photochromic effect is another example to illustrate the versatility of smart materials and the variety of their applications. A widespread use is for glasses which darken when exposed to the sunlight, protecting the user when it is necessary and turning back to its transparent state when ambient light decreases. It can also be used as an indicator of the intensity of UV radiation: in the form of bracelets, tattoos or clothes, they can indicate to the user which protection is adequate for the day. More sensitive versions of photochromic materials can also be used simply as colour changing jewellery, furniture and others, and will change colour as soon as they are exposed to natural light. Some examples are shown in the following figure (figure 7):

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Figure 7: Some applications of photochromic materials. From left to right: Adapting sun glasses, Reversacol, source: www.jamesrobinson.eu.com UV bracelets, Smartsun, source: <http://wristbands-lovers.blogspot.it/>. Colour changing t-shirt, www.solaractiveintl.com.

Applications of shape memory materials

When considering materials able to change shape, shape memory materials are the ones with the widest range of applications. These materials are able to recover their original shape when heated after a deformation. Other types of materials change their shape when submitted to a magnetic field, a chemical concentration, pressure or light.

This ability to recover their initial shape has led shape memory materials to be used in many technical applications, in particular in medical field, where they are tuned to recover their shape at body temperature. In this case, they are deformed before being applied, and then perform their functions when recovering their preset shape. They are also extensively used as actuators for mechanical systems or as joints in manufacturing processes (Talbot, 2003).

Beside these technical uses, some more visible applications that interact directly with users have been developed. For example, lighting furniture can take advantage of the heat produced by lamps to change shape when switched on; shirts containing shape memory threads can roll up its sleeves by itself when the user's body temperature increases.

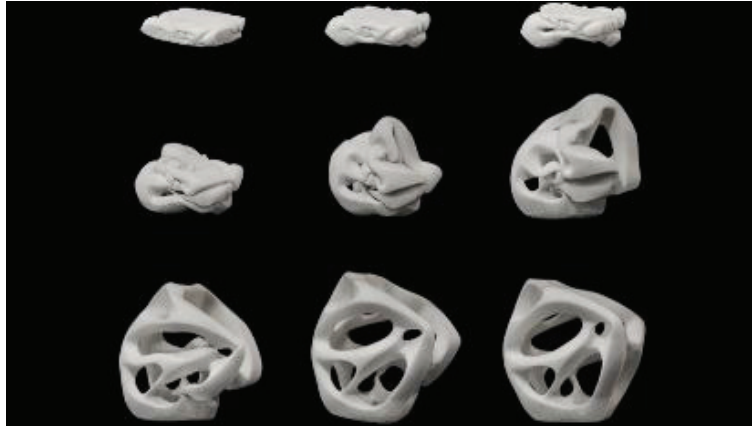


Figure 8: Shape memory chair, Noumenon by Carl de Smet, source: www.noumenon.eu.

Figure 8 present an experimental chair, which is stored is a flat shape representing 5% of its open shape. When heated above 70°C, it takes back its original shape. It can be compressed again and re-open.

Smart materials: discussion and prospects

As shown in the previous examples, their unique properties give each class of smart materials a wide range of applications. These applications can be either extremely technical or directly used to interact in a spontaneous way with the end users. These two different ways to use smart materials, in highly technical fields or for interaction with the end user, might seem really different, but in many cases, the very same effect can be used for both. For this reason, a link between technical and non-technical uses should be formalized, taking advantage of cross-fertilization and of aesthetic exploration to reinforce innovation in all potential fields of applications of smart materials.

A good way to improve the design practice related to smart materials will be to adapt information about smart materials in a way which can be directly used by designers. For that, it is first necessary to collect this information from material science publications and to put it all together. As demonstrated by the above examples, expressing the *functionality* of smart materials is more relevant to the design activity than conventional classifications by materials *families* or *properties*. Such an information

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system should however allow the comparison between solutions using smart materials with more conventional ones using structural materials. As such, the functional information contained in the system should be efficiently linked to conventional properties, in order to give a proper perspective to the designer.

Conclusion

In order to favour innovation in industry, it is necessary to strengthen the link between technical knowledge and design practices. There are nowadays a great number of materials that can be implemented in design projects, and it is necessary to have an idea of what exists to take advantage of all the possibilities of the materials world. It is especially true with materials that exhibit unusual behaviour, such as smart materials. Indeed, these materials are able to sense stimuli from their environment and to give an output depending on the incoming stimulus. If implemented in an efficient way, these materials can greatly enhance the interactions between a product and a user.

There are many different smart materials, and each of them exhibits a different behaviour. A first step to understand what can be done with these materials is to have an overview of the different types of available behaviours. An attempt to represent these types of behaviour has been presented in this paper, in the shape of a graph categorizing the materials by possible inputs and outputs, i.e., in terms of the added *functionality* brought forward by smart materials, instead of conventional *properties* or *structural* information such as given chemical classes. This classification allows to gather basic knowledge about the existing types of smart materials, and to identify which ones can be suited to a given project. In addition, precise information and examples of applications of the targeted smart material will be needed to successfully implement these it in a design project. Following this idea, we have presented some examples of applications of smart materials. We focused on applications that directly affect users' senses, since creating new user experiences is a main advantage of smart materials over common ones. Through these examples, we can notice that among a single class of materials, there are already different behaviours exhibited, differing for example by the continuous or sudden nature of their change in properties, or by the time needed for the change to occur. Smart materials can be used either for their functional

features, or for the enhanced user experience they can provide, which is related to the general framework of interaction design.

Since smart materials differ radically from common materials by being active instead of inert, they cannot be directly included in existing material selection tools, such as Granta Design's CES. Though, it would often be useful to compare smart and common materials when working on new projects. In this way, smart materials can be considered more systematically, without restricting the project to them when it is not relevant. To allow that comparison, further work will be needed to create a selection tool that includes both smart and common materials. Further information will be needed to select a precise material and use it properly and presenting this information in an efficient way will be the aim of further research.

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